AD 414163

DEFENSE DOCUMENTATION CENTER

FOR

SCIENTIFIC AND TECHNICAL INFORMATION

CAMERON STATION, ALEXANDRIA, VIRGINIA
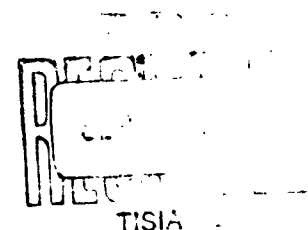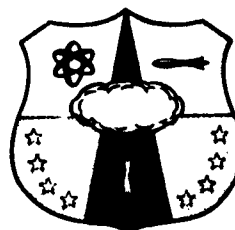
INSTRUMENTATION STUDY AND ANALYSIS FOR
OBSERVATION OF RE-ENTRY PHENOMENA

TECHNICAL DOCUMENTARY REPORT NUMBER AFSWC TDR 63-58

July 1963

TISIA

Development Directorate
AIR FORCE SPECIAL WEAPONS CENTER
Air Force Systems Command
Kirtland Air Force Base
New Mexico

FOREWORD

The author feels obligated to acknowledge the assistance of several organi-
zations and individuals without which the successful completion of the program
could not have been accomplished.

The technical staffs of both the Nuclear Power Division of the Air Force
Special Weapons Center's Development Directorate and the General Technologies
Corporation provided invaluable guidance and technical support in the conduct of
the program. The numerous personnel of the National Bureau of Standards and of
the National Aeronautics and Space Administration contributed freely of their time
in numerous discussions and correspondence.

The author is indebted to, and would like to thank, the following individu-
als for their assistance: Capt. C E Brunson of AFSWC for technical support and
guidance. Major Phillip McMullen for technical guidance and administrative
assistance in obtaining numerous reports and references. Majors H. W. Baker,
C. L. Brunson, and M Rozner, and Mr. John Ungvarsky for various technical dis-
cuss ons and for making it possible for the author to attend the RADNAPS Contrac-
tors' Meetings at San Diego, California on 7-9 August 1962, and at AFSWC on
16-18 October 1962; Mr. Thomas B. Kerr of NASA Headquarters and Lieutenant
Colonel W. K. Kern of the AEC for arranging for our attendance at the Aerospace
Physics and Re-entry Phenomena Meeting in Washington, D.C. on 6-7 December
1962; Dr. J W. Chamberlain at the Yerkes Observatory, University of Chicago,
for advice and information on re-entry optical phenomena; Dr. E. W. Adams,
NASA George Marshall Space Flight Center for suggestions on re-entry burn-up
models; R. L. Trimpi of NASA Langley for discussions and information on the
atmospheric re-entry environment associated with high velocity objects;
Dr. William F. Meggers and his associates for discussions on the optical spectra
of the elements; Mr. J. D. Graves, Dr. H. T. Wensel, and Mr. J. C. Withers
of the General Technologies Corporation who participated directly in much of
the analysis work presented in the report.

ABSTRACT

This work was undertaken to evaluate instrumentation and techniques for observing the phenomena associated with the atmospheric re-entry, at orbital or near orbital velocities, of NAP systems, with emphasis being placed on fuel element re-entry burn-up phenomena.

The uses of pyrometry, radiometry, spectrophotometry, and photography for determining the temperature of a re-entering body are analyzed. It is shown that all but the first of these methods can be used to obtain temperature information on re-entering objects that are not ablating. This temperature information is gained from measurements on the shape of the thermal emission curve. Methods for handling the ablating case are discussed.

The use of photography for identifying tracer flares that are re-entering the earth's atmosphere at high velocities was analyzed and shown to be feasible. How photography, in conjunction with tracer flare re-entry experiments, can be used for establishing the validity of mathematical, re-entry, burn-up models was also analyzed. The various associated difficulties and how they might be overcome are discussed in some detail.

PUBLICATION REVIEW

This report has been reviewed and is approved.

CLARENCE E. BRUNSON, III
Captain   USAF
Project Officer

PHILIP C. McMULLEN
Major   USAF
Acting Chief, Nuclear Power
Branch

RICHARD A. HOUSE
Colonel   USAF
Chief, Development Division

TABLE OF CONTENTS

I. INTRODUCTION

This report summarizes an instrumentation study and analysis performed by the General Technologies Corporation for the Nuclear Power Division of the Development Directorate of the Air Force Special Weapons Center under Contract No. AF 29(601)-5390. It is concerned almost exclusively with experiments and instrumentation that are related to the observation of optical phenomena associated with objects re-entering the earth's atmosphere at velocities up to 26,000 ft/sec.

During the program, the General Technologies Corporation, in cooperation with AFSWC personnel, studied the results of the over-all NAP systems re-entry program that is being conducted by AFSWC and the AEC*. These studies and analyses formed the basis for evaluating the various possible approaches to the optical instrumentation of the NAP system re-entry tests. The instrumentation studied included pyrometry, spectral photometry, ordinary photography in conjunction with filters, and spectral photography.

_____

*NAP is an acronym for Nuclear Auxiliary Power.

II. PROGRAM OBJECTIVES

The objectives of the program were three-fold: (1) to evaluate the instru-
mentation being utilized during NAP system re-entry tests, and, where possible,
to make recommendations for changes that might enhance the probability of success
in these tests; (2) to determine the reliability of various instrumentation for the
acquisition of data on various re-entry phenomena as specified by AFSWC; and
(3) to determine, if possible, other phenomena which should be measured in order
to enhance the utility of the flight tests' experiments toward establishing a re-entry
burn-up model for nuclear auxiliary power systems.

How these objectives were achieved is shown in the following technical
discussion section of this report.

III. TECHNICAL DISCUSSION

This section of the report will first discuss conventional (pyrometric, radiometric, and spectrophotometric) and photographic techniques for determining the temperature of a re-entering object, and then proceed with a discussion of the use of flaring materials for determining heat energy inputs to re-entering bodies.

A. CONVENTIONAL TEMPERATURE MEASURING TECHNIQUES

The problem to be considered is that of making temperature measurements on objects that are re-entering the earth's atmosphere at orbital or near orbital velocities. The measurements are to be made on instruments that are located within aircraft or in ground installations. The techniques to be considered are pyrometry, radiometry, and spectrophotometry. The theoretical bases for the operation of these instruments are the Wein displacement, Stefan-Boltzmann radiation, and Planck radiation laws of classical physics.

1. Theoretical Basis of Measurement

In order to make temperature measurements on re-entering bodies from ground or aircraft installations, it is necessary to resort to radiation measurements. Prior to discussing instrumentation for making such measurements, it is appropriate to first write down the theoretical basis for such measurements. Only three basic equations are needed to provide the basis for the analysis of appropriate instrumentation.

They are

$$P(\lambda, T) = \frac{\epsilon(\lambda, T) c_1}{\lambda^5 (e^{c_2/\lambda T} - 1)} \qquad \text{(Planck)} \qquad (1)$$

$$P(T) = \int_0^\infty P(\lambda, T) d\lambda = \epsilon_t \, c T^4 \qquad \text{(Stefan-Boltzmann)} \qquad (2)$$

$$\lambda_m T = 0.29 \qquad \text{(Wein)} \qquad (3)$$

$P(\lambda, T)$ = power emitted per unit area by a body at absolute temperature $T \, °K$ per unit wavelength interval at the wavelength λ.

$P(T)$ = power emitted per unit area from a body that is at the absolute temperature $T \, °K$.

$\epsilon(\lambda, T)$ = spectral emittance at the wavelength λ and temperature T. For a black body (total radiator), $\epsilon(\lambda, T) = 1$.

ϵ_t = total hemispherical emittance of the surface area under consideration. For a black body, $\epsilon_t = 1$.

λ_m = the wavelength in centimeters at which $P(\lambda, T)/\epsilon(\lambda, T)$ assumes its maximum value.

c_1, c_2, and c are constants. For the c.g.s. system of units:

c_1 = 3.741×10^{-5} erg-cm^2/sec, c_2 = 1.438 cm-deg., and

σ = 5.669×10^{-5} erg/cm^2-sec-deg^4.

Only two radiation measuring techniques lend themselves to the situation under consideration. They are the total radiation pyrometer and the spectrophotometer techniques. The radiometer is actually a variation on the spectrophotometer. Consider first the total radiation pyrometer, which is based on the principle of eq. 2.

4

2. Total Radiation Pyrometer

When a uniformly heated body of homogeneous composition and spherical shape is viewed at a great distance, total hemispherical emittance together with the atmospheric and inverse-square law effects will govern the amount of power available for measurement at the location of the pyrometer. It will have to be assumed that ϵ_t can be employed for bodies having geometrical shapes that are not spherical. If a lens system is to be used with the pyrometer, then the energy under consideration is that that is incident per unit area per unit time at the surface of the lens system. In order to write down the mathematical expression for this power, assume $\mu(\lambda)$ is the linear absorption coefficient of the air intervening between the source and point of measurement. Further, assume that there is no particulate matter in the light path so that build-up factors caused by multiple scattering need not enter the calculation, and that diffraction is so small that its effects can be neglected. Then the power per unit area at a large distance, R, from the source is

$$P(R, T) = \frac{A(R)}{2\pi R^2} \int_o^\infty \frac{c_1 \, \epsilon(\lambda, T) \, e^{-\mu(\lambda)R}}{\lambda^5 (e^{c_2/\lambda T} - 1)} \, d\lambda, \tag{4}$$

where A(R) is the total projected area of the source when viewed at the distance R. The R dependence of A reflects the possibility that the size of the object may change with distance along the re-entering trajectory. The factor $(2\pi R^2)^{-1}$ comes into play from the inverse square law and the fact that the projected area is radiating into a solid angle of 2π steradians. Now, to examine the integrand of

5

equation 4 in detail.

If it is assumed that, at the temperature T, $\epsilon(\lambda, T)$ is constant and $\mu(\lambda)$ does not vary significantly with λ, they can be factored out of the integrand to give, in accordance with equation 2,

$$P(R, T) = \frac{A(R)\,\epsilon_t}{2\pi R^2}\,e^{-\mu R}\sigma T^4, \quad \text{or} \quad T = \left[\frac{2\pi R^2 P(R)}{A(R)\,\epsilon_t \sigma}\right]^{\frac{1}{4}} e^{\mu R/4}, \tag{5}$$

where μ is the effective linear attenuation coefficient of the atmosphere for the light emitted by the body in question. This is the equation that one would have to work with if the total radiation pyrometer were to be used to try to measure the temperature of the re-entering body. The assumptions necessary to its derivation may be summarized as follows:

1. The range R is accurately known.

2. The body's surface area A is at a uniform temperature.

3. There is no significant quantity of particulate matter in the atmosphere to introduce multiple scattering of the light emitted by the body.

4. Refraction effects can be neglected.

5. The projected area, A, of the re-entering body is known at the time of measurement.

6. The body, insofar as its observed emission characteristics are concerned, behaves either as a grey body or one of spherical shape and homogeneous composition.

7. The emittance, ϵ_t, is accurately known under the conditions of measurement.

8. The linear absorption coefficient of air is essentially constant over the spectral range of interest.

The first four of these assumptions are considered to be reasonably valid.
The remaining four cast considerable doubt on the ability of total radiation py-
rometry techniques to gather more than qualitative information. According to
assumption 5, the projected area of surface being observed must be accurately
known. Since the body will, in general, be asymmetrical and will suffer con-
tinuous erosion during re-entry, this factor alone constitutes a serious problem for
nonspherical bodies.

The assumption that the body behaves as a grey body may be a serious one.
Whether or not this assumption is valid can be reasonably well determined by labo-
ratory measurements. Although ϵ_t can readily be measured in the laboratory up
to temperatures of 2300°K, and a considerable quantity of data is available for
temperatures up to this, it is doubtful that it wouid be available for any particular
materials selected at random. For materials whose temperatures will exceed 2300°K
during re-entry, ϵ_t will certainly not be known except in rare cases. Thus, assump-
tion 7, as well as assumption 6, requires one to resort to laboratory measurements.

Assumption 8, that $\mu(\lambda)$ = constant, is well known to be a poor one over the
spectral range that will be encountered. However, if assumption 6 can be established,
then the measured radiation reaching the pyrometer could be modified for the absorp-
tion by replacing μ in equation 5 with the relation

$$\mu = \frac{1}{\sigma T^4} \int_0^\infty \frac{\mu(\lambda) c_1 d\lambda}{\lambda^5 (e^{c_2/\lambda T} - 1)} \tag{6}$$

One would start with an assumed value of $\mu = \mu_0$, and solve eq. 5 for $T = T_0$. This

7

value of T would, in turn, be substituted into eq. 6, using the known values of

$\mu(\lambda)$ for air to obtain a better value of $\mu = \mu_1$. Substituting μ_1 into 5 again gives

a better value of $T = T_1$. This process can be reiterated as many times as is

necessary, depending upon the accuracy of the choice of μ_0, until an accurate

value of T is achieved.

In summing up, it can be said that, for a spherically shaped body whose total

hemispherical emittance is known, or a grey body, an accurate temperature measure-

ment can be made under idealized conditions with total radiation pyrometers provided

that spectral radiation from any associated heated gases or vapors is negligible.

To see how the accuracy of T depends upon the accuracy to which ϵ_t, $A(R)$, R,

and $P(R,T)$ are known, consider the following error analysis.

If $F = F(x, \ldots, x_n)$, then, according to the definition of total derivative,

$$dF = \frac{\partial F}{\partial x_1} dx_1 + \frac{\partial F}{\partial x_2} dx_2 \ldots + \frac{\partial F}{\partial x_n} dx_n . \tag{7}$$

If the second form of equation 5 is grouped according to variables, and these are

treated as being independent variables with $x_1 = R$, $x_2 = A$, $x_3 = P$, $x_4 = \epsilon_t$, and

$x_5 = \mu$, then, from eqs. 5 and 7,

$$\frac{\partial T}{\partial R} = \left(\frac{2\pi}{-} \right)^{1/4} \left(\frac{P}{A \epsilon_t} \right)^{1/4} \left[\frac{R^{-1/4}}{2} e^{\mu R/4} + \frac{\mu R^{1/4}}{4} e^{\mu R/4} \right] = \frac{T}{2R} + \frac{\mu T}{4}$$

$$\frac{\partial T}{\partial P} = \frac{T}{4P} ; \frac{\partial T}{\partial A} = -\frac{T}{A} ; \frac{\partial T}{\partial \epsilon_t} = -\frac{T}{\epsilon_t} ; \frac{\partial T}{\partial \mu} = \frac{RT}{4} .$$

8

Substituting these partial derivatives into eq. 7, dividing by T, and replacing dx_i with Δx_i gives

$$\frac{\Delta T}{T} = \left[\frac{1}{2R} + \frac{\mu}{4}\right]\Delta R - \frac{\Delta A}{A} + \frac{\Delta P}{4P} - \frac{\Delta \epsilon_t}{\epsilon_t} + \frac{R\Delta \mu}{4} \tag{8}$$

This equation clearly illustrates the important point that errors introduced in T by errors in μ will be dependent upon the range R, and that errors in T due to errors in R will be influenced by the value of μ. Thus, the larger the value of R or μ, the greater the error in T for a given fractional error in μ and R respectively. To see this, suppose $\frac{\Delta \mu}{\mu} = 0.01$ and $\mu = 0.04$. Then for $\Delta x_i = 0$ for $x_i \neq \mu$,

$$\frac{\Delta T}{T} = R\frac{\Delta \mu}{4} = \begin{cases} 0.01 \text{ for } R = 100 \\ \\ 0.1 \text{ for } R = 1000 \end{cases} \tag{9a}$$

In a similar manner, for $\Delta x_i = 0$ for $x_i \neq R$, $\mu = 0.04$, $\Delta R/R = 0.001$,

$$\frac{\Delta T}{T} = \left[\frac{1}{2R} + \frac{\mu}{4}\right]\Delta R = \begin{cases} 0.0005 + .001 = 0.0015 \text{ for } R = 100 \\ \\ 0.0005 + .01 = 0.0105 \text{ for } R = 1000. \end{cases} \tag{9b}$$

Thus, it is apparent that the error in T depends on the magnitude of both μ and R as well as the uncertainty in the values of these two parameters. These latter equations show that for large values of either μ or R, the temperature information becomes qualitative in nature.

The conclusion to be drawn from the foregoing analysis is that the total

radiation pyrometer technique has doubtful utility even under the best set of con-
ditions that could be reasonably assumed in the intended application.

3. Spectral Photometry Techniques

The application of spectrophotometry techniques should be considered under
two separate conditions. The first of these is where the re-entering body exhibits
the grey body spectrum, that is $\varepsilon(\lambda, T)$ is a constant throughout the wavelength inter-
val in which observations are necessary for determining the temperature. The second
case involves the non-black body spectral distribution and, where a knowledge of
the spectral emittance is missing, becomes insoluble except when special attention
is given to the emission spectrum curve.

It is clear from the foregoing discussion that the atmospheric absorption must
be taken into consideration in using the spectrophotometric technique. However,
since the principle involved is identical to that just discussed, it will be left out of
the formulation in order to preserve simplicity of presentation.

3.1 Grey body spectrum case.

This case can also be broken into two sub-cases, where the emission peak
alone is considered and where two points away from the peak are considered.

3.1.1 Emission peak sub-case.

In this case, eq. 3 is the commanding relation. The relative intensity of
the entire spectrum, or at least a portion of the spectrum that extends considerably

10

beyond the peak emission wavelength, $\lambda_m = 0.29\,T^{-1}$, on both sides of the peak, is recorded spectrophotometry-wise. If this peak lies in the vicinity of the air absorption curve where $\mu(\lambda)$ is constant, then

$$T = 0.29\,\lambda_m^{-1} \quad \text{for}\ \mu(\lambda) = \text{constant}. \tag{10}$$

For the case where $\mu(\lambda)$ is not constant in the region of the apparent peak, a reiterative process (as exemplified in paragraph 2, following eq. 6) must be resorted to. This is accomplished as follows. Viewing the absorption and measured emission curves, a value of $\lambda_m = \lambda_{mo}$ is chosen, and $T = T_0 = 0.29/\lambda_{mo}$ is calculated. This value of T_0 is used to manufacture a new emission curve $P(\lambda, T_1)$ using the relation

$$P(\lambda, T_1) = P(\lambda, T_0)\,e^{-\mu(\lambda)R}. \tag{10a}$$

Here $P(\lambda, T_0)$ is taken from eq. 1, with $\epsilon(\lambda, T)$ set to unity. This new curve will peak at some value of $\lambda = \lambda_{m_1}$. Using this value of λ_{m_1} and eq. 10a, T_1 is computed. Using this value of $T = T_1$, the second-order approximation of $T = T_2$, is determined from the curve generated by the relation

$$P(\lambda, T_2) = P(\lambda, T_1)\,e^{-\mu(\lambda)R}.$$

The n th order approximation of $T = T_n$ is obtained from the curve plotted from the relation

$$P(\lambda, T_n) = P(\lambda, T_{n-1})\,e^{-\mu(\lambda)R}, \tag{10b}$$

where $P(\lambda, T_{n-1})$ is taken as having the functional form of eq. 1 with $\epsilon(\lambda, T) = 1$.

Hence $\quad T_n = 0.29/\lambda_{mn}.$ \hfill (10c)

The value of n required to obtain a stationary value for the manufactured emission peak will depend upon the judiciousness with which the initial value of $T = T_o$ is chosen. Unless $\mu(\lambda)$ is varying drastically in the vicinity of λ_{mo}, one should not need to use values of n greater than 2 or 3. It would perhaps be useful to plot the ratio of $P(\lambda, T_n)$ to the initially measured curve. When this ratio approaches a straight line in the vicinity of the peak, one is assured that a sufficiently large value of n has been achieved.

The assumptions employed to derive equation 10c are much less capricious than those used in the derivation of eq. 5. For equation 10c, the assumption is that $\epsilon(\lambda, T)$ = constant in the vicinity of λ_m. For eq. 10, the assumptions were that $\epsilon(\lambda, T)$ and $\mu(\lambda)$ are both constant in the vicinity of λ_m. For a given value of λ_m, the validity of the proposition that $\mu(\lambda)$ is constant can be determined from atmospheric absorption data. The validity of the assumption that $\epsilon(\lambda, T)$ is a constant in the region of λ_m is something that will have to be determined by laboratory experiments.

3.1.2 Two-point or ratio technique with $\epsilon(\lambda, T)$ known.

When $\mu(\lambda)$ is not constant, it is more convenient to use the ratio technique. Here two separate points on the emission curve are chosen, say at λ_1 and λ_2. Then using eq. 1 and the exponential atmospheric absorption relation, T is determined by the equation,

$$\frac{P(\lambda_1, T)}{P(\lambda_2, T)} = \frac{\epsilon(\lambda_1, T)}{\epsilon(\lambda_2, T)} \left[\frac{\lambda_2}{\lambda_1}\right]^5 \left[\frac{e^{c_2/\lambda_2 T} - 1}{e^{c_2/\lambda_1 T} - 1}\right] e^{\left[\mu(\lambda_2) - \mu(\lambda_1)\right]R} \tag{11}$$

12

This is essentially the basis for the operation of the two-color pyrometer. The only assumptions required are that the body is either grey or $\epsilon(\lambda_1,T)$, $\epsilon(\lambda_2,T)$, are known and that $\mu(\lambda_1)$ and $\mu(\lambda_2)$ are known.

In view of the fact that materials tend to become spectrally greyer at elevated temperatures when the line spectra are subtracted, this technique holds considerable promise for obtaining quantitative temperature information on a wide variety of re-entering materials.

3.2 The non-grey body case without $\epsilon(\lambda,T)$.

It is now appropriate to see what can be done in case experiments should show that $\epsilon(\lambda,T)$ is neither constant nor known. In other words, what can be determined if emittance data is completely lacking. If the power emission curve is recorded as in the preceding case, two points on this curve can be employed to obtain an expression involving only one unknown, namely T, if they are appropriately chosen. By viewing the $P(\lambda, T)$ vs. λ curve, there will be one or more wavelength intervals over which the emission curve can be accurately approximated by a straight line. Over such a portion of the emission curve, the wavelength derivative of $P(\lambda, T)$ will be constant. This suggests the use of a Taylor expansion of $\epsilon(\lambda,T)$ in this interval, which can, in turn, be substituted into eq.1 to obtain the temperature. In this case, since the temperature is considered to be a constant for a given spectral curve, the temperature dependence of ϵ may be dropped from the notation. To this end, consider the following.

Let $\dfrac{dP(\lambda, T)}{d\lambda} = P' = $ constant through the interval λ_o to λ Hence

$$\frac{d^n P(\lambda, T)}{d\lambda^n} = 0 \text{ for } n > 1 \text{ in the interval } (\lambda_o, \lambda). \tag{12}$$

If the interval (λ_o, λ) is small, $\epsilon(\lambda)$ can be expanded about λ_o in a Taylor series as

$$\epsilon(\lambda) = \epsilon(\lambda_o) + \frac{(\lambda - \lambda_o)}{1!} \frac{d\epsilon}{d\lambda}\bigg|_{\lambda = \lambda_o} + \frac{(\lambda - \lambda_o)^2}{2!} \frac{d^2\epsilon}{d\lambda^2}\bigg|_{\lambda = \lambda_o} + \cdots \; . \tag{13}$$

For a given value of T, equation 1 defines $\epsilon(\lambda)$ as

$$\epsilon(\lambda) = P(\lambda, T)\, \phi(\lambda, T), \tag{14}$$

where

$$\phi(\lambda, T) = \frac{\lambda^5 (e^{c_2/\lambda T} - 1)}{c_1} \tag{15}$$

It follows that

$$\epsilon(\lambda_o) = P(\lambda_o, T)\, \phi(\lambda_o, T), \tag{16}$$

and that

$$\frac{d\epsilon}{d\lambda}\bigg|_{\lambda = \lambda_o} = P(\lambda_o, T) \frac{d\phi(\lambda, T)}{d\lambda}\bigg|_{\lambda = \lambda_o} + \phi(\lambda_o, T)\frac{dP(\lambda, T)}{d\lambda}\bigg|_{\lambda = \lambda_o} \; .$$

In view of the fact that the higher derivatives of $P(\lambda, T)$ are zero, the higher derivatives of $\epsilon(\lambda)$ can be written down immediately as

$$\frac{d^n \epsilon}{d\lambda^n}\bigg|_{\lambda = \lambda_o} = n\, P'(\lambda_o, T)\, \phi^{(n-1)}(\lambda_o, T) + P(\lambda_o, T)\, \phi^{(n)}(\lambda_o, T), \tag{17}$$

14

where the notation $\dfrac{d^m \phi(\lambda,\ T)}{d\lambda^m}\bigg|_{\lambda=\lambda_o} = \phi^{(m)}(\lambda_o,\ T)$ has been used. Substituting

equations 16 and 17 into eq. 13 gives $\epsilon(\lambda)$ in terms of the chosen wavelengths

λ_o, λ, the measured emission power at λ_o, the measured slope of the curve at

λ_o and the unknown T. Substituting this value of $\epsilon(\lambda)$ into equation 1 gives the

desired expression in T. That is

$$P(\lambda,\ T) = \frac{c_1 K\left[(\lambda-\lambda_o)\ P'(\lambda_o,\ T) + P(\lambda_o,\ T)\right]}{\lambda^5(e^{c_2/\lambda T}-1)} \tag{18a}$$

where

$$K = \sum_{n=0}^{\infty} \frac{(\lambda-\lambda_o)^n}{n!}\left[\frac{d^n}{d\lambda^n}\frac{1}{\tau(\lambda,\ T)}\right]_{\lambda=\lambda_o}. \tag{18b}$$

The only unknown in eq. 18 is the temperature T, hence, the emittance is eliminated. Thus, even when the spectral emittance of the re-entering body is unknown, its temperature can be computed from the spectral emission curve by a judicious choice of λ_o and λ where the quantity $(\lambda-\lambda_o)$ is chosen sufficiently small to assure the rapid convergence of the K-series of eq. 18b. Further analysis shows that the series converges more rapidly for shorter wavelength regions of the spectral curve, that is, on the short wavelength side of the emission peak.

It is evident that one of these three techniques can be used to determine the temperature providing that the spectral emission curve can be obtained.

3.3 Unscrambling the spectral emission curve.

The object is to devise a method whereby the spectral emission produced by

the gases and vapors associated with the re-entering body can be separated from the observed spectral emission curve. For the sake of preserving clarity, the emission from the re-entering body proper will henceforth be referred to as the thermal emission curve. The observed spectrum (curve) from a re-entering body will contain three components, namely

1.   The thermal emission curve.

2.   The emission from the heated air.

3.   The emission from the vaporized materials.

The thermal emission curve was discussed briefly above and is described by equation 1.

Up to temperatures where vaporization and ablation of the re-entering object become important, one need only consider the optical emission of the air in order to unscramble the thermal emission curve from the observed spectrum. The theoretical basis for treating both the heated air and heated vapors emanating from the surface of the re-entering object is the same, so they will be considered simultaneously. The reader will bear in mind at all times that the nonablative (or evaporative) case is much the simpler of the two and is believed to be well within the present state of the art from both a theoretical and experimental point of view.

The principal mechanisms which produce light in the heated material associated with the re-entering body (i.e., gases and vapors) are:

1. Excitation due to thermal collisions with the heated molecules within the shockwave. Here, within the shockwave refers to the wake as well as the volume between the shock front and boundaries of the re-entering body.

2. Chemical reactions which emit light.

3. The optically stimulated transitions produced by nearby sources of light.

4. Excitation by impact with uncharged air molecules.

5. Excitation by collisions with charged particles.

In considering the thermal collisions, one can readily set an upper bound to the quantity of radiation that it is possible to produce from the kinetic theory of gases. It can readily be shown from the kinetic theory of gases that the fraction of molecules having a velocity, v, greater than some specified velocity, v_o, is given by

$$\frac{N(v \geqslant v_o)}{N} = v_o \sqrt{2m/\pi kT} \; e^{-m v_o^2/2kT} + \sqrt{m/kT} \left[\frac{2}{\sqrt{2\pi}} \int_{v_o}^{\infty} \sqrt{m/kT} \; e^{-\alpha^2/2} d\alpha \right] (19)$$

The quantity in brackets is just $1 - P(x)$, where $P(x)$ is the normal probability function and is tabulated for all values of the argument of interest.

By setting $v_o = \sqrt{2h\nu/m}$, where $h\nu$ is the energy of the photon to be emitted, eq. 19 gives the fraction of the molecules that would possess sufficient energy to produce an excited state from which radiative transitions might occur. In view of the simplicity of this equation, one can readily perform experimental measurements to determine the probability per collision as a function of v that a collision will

17

occur which produces an excited state from which a radiative transition occurs.

In most practical cases, this process of stimulated emission will be small. There

is a considerable quantity of data to draw from in evaluating this phenomena.

Most chemical reactions will produce little light, and this can readily

be determined from the literature or simple experiments. Thus, this source of

light is no problem.

If the intensity of a single line in a spectrum is known, then the relative

intensities of other lines, $I(\nu)$, can be calculated[1]*. This is illustrated by the

relation

$$\frac{I(\nu_1)}{I(\nu_2)} = \frac{N(\beta_1)}{N(\beta_2)} \frac{\nu_1^4 S(\alpha_1, \beta_1)}{\nu_2^4 S(\alpha_2, \beta_2)} \tag{20}$$

where $N(\beta)$ is the number of molecules in state β, and $S(\alpha, \beta)$ is the Condon-

Shortley line strength[2].

In view of the fact that optical transitions involve Einstein's A and B co-

efficients, and of the fact that the A coefficient is derivable from the B coefficient,

and vice versa, it is convenient to define the quantity $\bar{S}(i, \beta)$, as the probability of

a spontaneous de-excitation transition from state (or level) i to state (or level) β,

and $S(\alpha, i)$ as the stimulated excitation transition probability from level α to level

i. It is understood that one is derivable from the other, and that the number of

sub-states in a level is just the weighted sum of $(2J + 1)$ times the number of levels,

where J is the total angular momentum quantum number of the level. The optically

stimulated radiation arising from transitions from the level β to the level α can then

---

*Numbers in parentheses represent references at the end of the text.

be written down immediately from the following considerations[3,4,5].

Assume that α is the ground level, and the transition from level β to level α is the one of interest. For an exciting intensity $I(\nu)$, the total rate of excitation from the ground level is simply $I(\nu)N(\alpha)\alpha(\nu)$, where $\alpha(\nu)$ is the linear absorption coefficient of the material containing the states α. Hence, the number of molecules (or atoms) excited directly to the level β is $I(\nu)N(\alpha)\alpha(\nu)S(\alpha,\beta)$. Since the mean life of a molecule (or atom) in the excited state β is on the order of 10^{-7} to 10^{-8} seconds, one may assume that the radiation intensity from the transition β to α is equal to the rate of excitation into state β. The excitation to these levels is simply $I(\nu)N(\alpha)\alpha(\nu) \Sigma S(\alpha, i)$ where the summation extends from $i = \beta + 1$ to some number n determined by the upper energy limit to which ν is capable of producing excitation. Some of these will de-excite to level β and hence to level α, producing the resonant line frequency ν_0 (actually $\nu_0 \pm \Delta\nu$). Since $\bar{S}(i, \beta)$ is the spontaneous transition probability from level i to level β, the quantity $I(\nu)N(\alpha)\alpha(\nu) \Sigma S(\alpha, i)$ must be multiplied by it to obtain this contribution to $I(\nu_0)$. Now, all molecules in level β are postulated to spontaneously decay to level α so that the total intensity of frequency ν_0 from optical stimulation is

$$I(\nu_0) = I(\nu)N(\alpha)\alpha(\nu)\left[S(\alpha,\beta) + \sum_{i=\beta+1}^{n} S(\alpha, i)\bar{S}(i,\beta)\right]. \tag{21}$$

This can be normalized to give the fraction of excited atoms that emit the resonant frequency by dividing by $\Sigma S(\alpha, i)$, for $i = \beta$ to n. It is to be understood that the

19

TDR 63-58

intensity of the resonant frequency represents the intensity of all optically pro-
duced transitions from level β to level α. Thus, ν_0 will exhibit structure when
either α or β have sub-levels. For atomic spectra, the summation over these sub-
levels can be treated as a single line for the most practical cases. It is perhaps
pertinent to add the relation for $\alpha(\nu)$. That is,

$$\alpha(\nu) = \frac{\pi e^2}{mc} f_{\alpha\beta} \frac{\Gamma_{\alpha\beta}/4\pi^2}{(\nu-\nu_0)^2+(\Gamma_{\alpha\beta}/4\pi)^2} \tag{22}$$

where

$$f_{\alpha\beta} = \frac{8\pi^2 m\nu}{3he^2} \frac{S(\alpha,\beta)}{2J_\beta+1} . \tag{23}$$

Here $\Gamma_{\alpha\beta}$ is the reciprocal of the mean life of state β for decay to state α.

The case of collision produced excitation can be treated in a quite analo-
gous manner. It can readily be shown that a similar argument leads to the follow-
ing relation for collisional excitations.

$$I(\nu_0)_r = N(\alpha)\left[\sum_{i=\beta+1}^{n}\bar{S}(i,\beta)\int_0^\infty \rho_r f_r(v)Q_{\alpha i}(v)dv + \int_0^\infty \rho_r f_r(v)Q_{\alpha\beta}(v)dv\right], \tag{24}$$

where ρ_r is the density of the i th species of atom (molecules, ions, electrons)
producing the excitation, $f_r(v)$ is the velocity distribution of these atoms relative
to the atom (or molecule) with which they are colliding, and $Q_{\alpha\beta}(v)$ is the cross
section at the velocity v for a transition from level α to β. Obviously equation
24 must be summed over all r in order to give the total emission due to collisions
of the molecules (atoms) in question with each of the r different species present

20

in the medium.

The above discussion was intended to be rather general; however, rigorous derivations of the formulae presented are derived in the references cited.

The geometry of the volume of material has been neglected (optical thickness), the nonuniformity of the thermal conditions, the depletion of states due to excitation, the nonequilibrium conditions due to changing environment during re-entry, etc., have all been neglected. However, one does not find it difficult to imagine that these can all be treated in either an exact or an approximate manner that will be sufficiently satisfactory to permit quantitative temperature information to be derived.

The literature and experimental data that presently exist are expected to yield sufficient information to permit a determination of the feasibility of the approach in the nonablative case. A cursory glance at the literature shows that suitable wave functions and data are available for evaluating the line strengths of O_3, O_2, O_2^-, O^-, N_2, NO, NO_2, A, CO_2, and for collisions with electrons for H, O_2, O, N_2, the one electron (alkali) atoms, and others. It is worthy of note that Kivel and Bailey[6] were able to construct a reasonable model (neglecting atomic spectra) for the emissivity of air as long ago as 1957. Furthermore, the composition of air in the shock wave has been fairly well established by Trimpi and Jones[7], Witliff and Curtis[8], and others.

In conclusion, it is apparent that any one of the three spectrophotometric techniques discussed (emission peak detection, ratio technique, nongrey body case)

will successfully determine the temperature of a re-entering body provided that the line spectrum can be subtracted from that part of the total spectrum being viewed. The analysis on unscrambling the thermal emission curve from the total emission curve indicates that although the efforts would be laborous, a good approximation of the thermal emission curve could be obtained at least in the non-ablating re-entry case. Thus, quantitative temperature information could be obtained from either of the techniques. For the ablative case, one would have to resort to experiments to determine the intensities of the spectral lines that must be subtracted from the thermal emission curve in order for these approaches to work.

B. PHOTOGRAPHIC TEMPERATURE MEASURING TECHNIQUES

Spectral photographic techniques offer every advantage that spectrophotometry offers and suffer from the same physical restraints. Photography without spectometry is equivalent to total radiation pyrometry.

When ordinary photographs of a re-entering body are taken and the density on the developed negative is read with a densitometer, the signal received is proportional to the logarithym of the intensity of the light to which the plate was exposed, whereas the total radiation pyrometer gives a signal which is proportional to the intensity of the incident light. Hence, the two methods are essentially equivalent. Thus, this approach to measuring the temperature of a re-entering body has very limited utility and little to recommend its use.

When the negative from a spectral photograph is read on a densitometer,

22

the result is a functional plot whose amplitude is proportional to the logarithym of

the intensity at each wavelength of the light that was incident upon the plate.

From a knowledge of the spectral sensitivity of the photographic plate, its densi-

tometer trace can be converted directly into an intensity versus wavelength curve

that is identical to that that would be recorded on a spectrophotometer under the

same conditions. Therefore, the same methods (grey body case, emission peak case,

ratio technique, and non-grey body case) discussed under the spectrophotometric

method are applicable. Of course, limitations, such as atmospheric absorption

and the spectral emission curve unscrambling, are also applicable.

A major advantage of the spectral photographic method for measuring

temperature, when compared with the spectrophotometric method, is its inherently

greater speed. Spectrophotometers require from a few seconds to a few minutes

to generate a spectral curve, whereas a spectral photograph may be taken in a few

milliseconds. This higher speed assures that the temperature of the re-entering

body will not change appreciably while the measurement is being made.

C. USE OF FLARES FOR DETERMINING HEAT INPUT

There are two types of flares that may be used to determine the rate of heat

input to a re-entering body. One is the ignition flare, and the other is a "burn-

up" or "tracer" type of flare. Since the former of these renders only the "single

point" type of information, the technical part of this discussion will be limited to

the tracer flare. Since the primary purpose of the flare experiments of interest to

AFSWC, the AEC, and their contractors is to determine the validity of certain mathematical, re-entry, burn-up models for nuclear auxiliary power system fuel elements, the discussion will be limited primarily to this application of tracer flares.

The use of tracer flares to check the validity of re-entry, burn-up models for fuel elements is predicated upon the following proposition: Flares having physical characteristics similar to those of the fuel elements can be constructed; the flare burn-up profile (altitude, velocity, brilliancy, etc.) is calculated using the same mathematical model used to calculate the burn-up of the fuel elements; and the flares can be subjected to flight tests that closely simulate those to which the fuel element is expected to be exposed. If the flare is observed to behave in the manner predicted by the model, this raises the confidence in the model's predictive capability. The objective of the present study was to evaluate the instrumentation techniques that are appropriate for observing the re-entry of such flares and how such observations might be interpreted to yield useful information on the re-entry, burn-up model. To this end, it is appropriate to first develop an analytical model for the phenomena to be observed and then see what ramifications are required in order to apply it to an experimental re-entry test.

1. Analytical Model for Flare Observing Instrumentation

In view of the facts that photography is the most readily applicable method for observing re-entering flares, and that other techniques which make use of the

24

radiation emitted by the re-entering flare can be reduced to the principles involved in photography, the discussion will be limited to photographic techniques. Further, because the use of a movie camera and a camera with open shutter will yield essentially the same information, the camera shutter will be assumed to remain open so as to generate a trace of the re-entering flare on the photographic plate.

The camera will respond to two sources of light, the thermal radiation from the heated re-entering flare, $P(R,T)$, as represented by eq. 4, and the light, $I(R, \lambda)$, that is emitted by the air, and vaporized and chemical products from the flaring materials (and the materials in which it is capsulated if it is a capsulated flare). If flaring materials whose vapor pressures are high at relatively low temperatures are employed, then the thermal radiation, $P(R,T)$, will be negligibly small. It will be assumed hereinafter that such is the case. To apply the results to cases where the thermal radiation is not negligible, all that one needs to do is replace $I(R, \lambda)$ by $\left[I(R, \lambda) + P(R, \lambda) \right]$ in the formulae that follow. With this in mind, the density of the plate produced by flare X, containing m elements, as viewed by a densitometer, can be written as

$$D(R, X) = \log\left[\sum_{s=1}^{m} \sum_{i=1}^{n} F_a (R, \lambda_i) \, F_c(\lambda_i) \, F_f(\lambda_i) \, I_s(\lambda_i, R, X) \right] \qquad (25)$$

where

$F_a(R, \lambda_i)$ = fraction of the light emitted at the wavelength λ_i that is transmitted through the atmosphere the distance R to the camera lense.

$F_c(\lambda_i)$ = fraction of the light of wavelength λ_i incident at the camera that is transmitted through the lens-filter system to the photographic plate.

25

$F_f(\lambda_i)$ = film sensitivity at the wavelength λ_i, that is, the number of silver ions activated per unit intensity of incident light at the wavelength λ_i.

$I_s(R, \lambda_i, X)$ = intensity of the light emitted at the wavelength λ_i by the m materials in the flare at the point R along the trajectory. (Actually, it is the amount of light energy emitted at the wavelength λ_i, over a portion of the re-entry trajectory that corresponds to the slit width of the densitometer sensing head). The subscript s is used to denote the different materials in flare X.

The summation of i is to be taken over all spectral lines emitted by each of the m re-entering flare materials. A further simplification of this relation can be made from the fact that the intensities of all lines from a single element in the flare can be written in terms of the intensity of a single reference line from that element[1]. If this reference line is designated as λ_{rs} for the s th element in the re-entering flare, then the intensity from any line, λ_i, from the s th element in flare X can be written as

$$I_s(R, \lambda_i, X) = C_{is} I(R, \lambda_{rs}). \tag{26}$$

Here C_{is} is a constant that has been tabulated[1] for every element, s, of interest. It should be pointed out here that the relative values of C_{is} given in reference 1 are valid only for a given element, s. The tabulated ratio of two line intensities from two different elements, say C_{1i}/C_{1s}, is not valid for re-entry applications. If the further contraction in notation,

$$G(R, \lambda_i) = F_a(R, \lambda_i) F_c(\lambda_i) F_f(\lambda_i), \tag{27}$$

is made, eq. 26 can be substituted into eq. 25 to give

$$D(R,X) = \log\left[\sum_{s=1}^{m} I(R, \lambda_{rs}) \sum_{i=1}^{n} G(R, \lambda_i) C_{is}\right]. \qquad (28)$$

Now all of the quantities under the second summation sign in this equation can be calculated from a knowledge of the atmospheric attenuation at the distance R, the lense system and filters, and tabulated spectral line intensities. Therefore, for a given value of s (i.e., for a given element in the flare), it is convenient to set this summation equal to the known constant $C_s(R)$. When this is substituted into eq. 28, the result is

$$D(R, X) = \log\left[\sum_{s=1}^{m} C_s(R) I(R, \lambda_{rs})\right]. \qquad (29)$$

The problem is now reduced to one of determining the intensity of the reference line λ_r for each of the m elements contained in the flaring material at each point along the trajectory R.

2. Application to Burn-Up Model Validification

It is at this point that the analysis runs into difficulty. As mentioned above, the intensity of a line is determined by optically stimulated transitions (eq. 21, 22, 23) and by impact phenomena (eq. 24). Thus, only such materials as those listed on page 21 can be handled directly from first principles without resorting to experiments to determine transition probabilities and collision cross sections.

This brings up the important consequence that, without a knowledge of $I(R, \lambda_{rs})$, nothing can be ventured as to how much flaring material should be used to produce a desired flare intensity. Therefore, the intensity of the light from a

27

flare alone cannot, in general, be employed as a measure of heat input at any particular time to a re-entering object without resorting to some rather fundamental experimental work.

These difficulties do not prohibit the use of flares if an adequate burn-up model is available. For example, if the burn-up is one simply of vaporization, then the rate of vaporization would be proportional to the rate of heat energy input to the flaring object, and the length of time that the flare would be visible would equal the time required for the heat energy input to equal the total heat of vaporization of all of the flaring material. In addition, the intensity of the light along the track would be expected to be approximately proportional to the product of the amount of flaring material deposited per unit track length interval and the square of the velocity of the flare. Usually an atom will emit essentially all the light that it is going to emit within a very short distance (within the photographic resolution) of the point of vaporization. Since the amount of flaring material per unit track length is proportional to the heat energy input to the flare, per unit track length, dq/vdt, the intensity at the position R along the trajectory would be expected to be approximately proportional to $v(R) \, dq/dt$. The validity of this last assumption would depend upon the amount of light emitted by a vaporized flare atom being proportional to its kinetic energy (relative to the surrounding air molecules) at the time of evaporation.

This analysis shows that, under the conditions assumed, both the duration and intensity profile of the flare trajectory could lend support to the validity of a

burn-up model. The word support is underlined because the correlation between the measured and predicted path length and intensity profile does not prove the validity of the burn-up model. Becuase of the fact that the mechanism whereby the flaring material is caused to emit light is not known, this correlation merely shows that the observation does not disprove the model. However, if the length of the trajectory does not agree with that predicted by the model, this would not necessarily disprove the validity of the model because the rate of evaporation at which the flare should first become visible and finally become invisible will be unknown unless $I(R, \lambda_{rs})$ can be calculated.

The up-shot of this discussion is that unless measures are instituted whereby $I(R, \lambda_{rs})$ can be determined, the use of tracer flares cannot positively prove or disprove a mathematical model of re-entry burn-up. It is possible, however, through the institution of appropriate experimental tests, to determine $I(R, \lambda_{rs})$. In fact, if the re-entry environment can be accurately specified, one would be able to calculate $I(R, \lambda_{rs})$ from first principles for the hydrogen-like elements, such as alkali metals.

An important point should be brought up here. If the length and position of the visible trajectory and its intensity profile do correlate well with that predicted, then one can make the assumption that it is correct and proceed to calculate $I(R, \lambda_{rs})$. With this information, one can then devise a re-entry experiment that is significantly different from the initial experiment but that is based upon the same mathematical, re-entry, burn-up model. If the data from this experiment

correlates closely with that predicted, one would not only be confident of the accuracy of the mathematical model but would also have gained valuable information on the reactions which give rise to the emitted light.

The confidence in the predictive capability of the model in fuel element applications would, of course, depend upon how closely the physical characteristics of the test flares approach those of the fuel elements. (Physical characteristics here mean size, shape, density, chemical properties, mechanical properties, thermophysical properties, etc.) If these two sets of characteristics differ markedly, one has no assurance that the mechanisms of failure and burn-up would be similar for the flare and fuel element.

3. Identification of Multiple Simultaneous Flares

During actual re-entry tests, it is the general practice to have several flares re-entering simultaneously along closely spaced trajectories. One would like to use photographic means for determining which observed trajectory corresponds to which flare. To simplify the analysis without loss of principle, each flare will be assumed to contain only one element. Under these conditions, X may be set equal to s in eq. 29, which can then be rewritten as

$$D(R, s) = \log\left[I(R, \lambda_{rs}) C(R) \right] = \log I(R, \lambda_{rs}) + B_s \qquad (30)$$

where $B_s = \log C_s(R)$ is a constant that can be calculated from the film sensitivity, camera lens-filter system, the tabulated relative line intensities[1] and $I(R, \lambda_{rs})$ once

30

s and R are specified. It will be sufficient to use only two simultaneous, single element flares to illustrate the principle of identification. Designating these two elements by $s = 1$, and $s = 2$, eq. 30 can be used to write two equations, namely

$$D(R_1, 1) = \log I(R_1, \lambda_{r1}) + B_1 \tag{31a}$$

$$D(R_2, 2) = \log I(R_2, \lambda_{r2}) + B_2 \tag{31b}$$

where λ_{r1} and λ_{r2} are the chosen reference lines for flare #1 and #2 respectively, and $D(R_1, 1)$ and $D(R_2, 2)$ are the observed densities on the photographic plates (open shutter case) that correspond to the positions R_1 and R_2 along the respective trajectories. The subscripts on R are used to indicate that the trajectories of the two flares will not necessarily be identical Now it is a fact that $D(R_1, 1)$ and $D(R_2, 2)$ will each start at zero, rise to some peak value and then decrease to zero provided the flares burn up during the trajectories. Therefore, each of the traces on the photograph will contain an infinite set of values of densities. Since the relative magnitudes of $I(R_1, \lambda_{r1})$ and $I(R_2, \lambda_{r2})$ are unknown (unless they have been calculated or measured under simulated re-entry conditions), no information can be gained from the traces that will identify which of the two streaks corresponds to flare #1. However, if two photographs are used, one of which sees the light from one and only one of the flares, while the other sees the light from both, then positive identification is readily made. It is assumed here that time and positional information are available on both photographic plates.

This identification can be generalized to n-flares. If n photographs are made on n cameras, each of which is filtered to pass the light from one and only one flare, then it is obvious that each of the n flares would be uniquely identified. Alternatively, and more readily realizable, if n photographs are taken, each of which extinguishes the light from a different flare, positive identification is again possible. That is, each flare is identified by its absence on a particular plate. It is important to note that no number of photographs, each of which contains a trace from every one of the flares, is sufficient to permit the positive identification of any flare when more than one flare appears simultaneously.

In the case where each flare emits a predominantly different color of light, a single color photograph which produces true colors would be sufficient to uniquely identify each flare. Similarly, a snapshot spectral photograph could be employed to identify each flare provided the spectra from no two of the flares are superimposed on the photograph.

The pertinent conclusions to be drawn from the foregoing discussion are summarized in the following section.

IV. CONCLUSIONS

TOTAL RADIATION PYROMETRY TEMPERATURE MEASUREMENTS

For either a spherically shaped body whose total hemispherical emittance is known, or a body that exhibits grey-body emission characteristics, measurements with a total radiation pyrometer can be used to accurately determine temperature provided that the range to the body and the absorption of the emitted light by the atmosphere intervening the instrument and object are small and accurately known. The situation in which line spectra from the ablated products and the heated gas-cap in front of the re-entering object cannot be neglected must also be precluded from consideration for this case. The accuracy with which the temperature can be determined is dependent upon the magnitudes of the atmospheric absorption and the range of the object being viewed as well as the inaccuracies in these two parameters. The analysis has shown that the pyrometric technique has very limited utility, and other than being quite simple, has little to recommend its use.

SPECTROPHOTOMETER TECHNIQUE FOR TEMPERATURE MEASUREMENTS

The spectrophotometer is adequate for measuring the temperature of a re-entering body, provided that the spectra from gases and vapors, associated with the re-entering object, can be subtracted from the total spectral emission curve recorded on such a device to yield the thermal emission curve. (The latter is described by eq. 1.) In non-ablating cases, the spectra that produce the total emission curve can

be unscrambled to yield the thermal emission curve. This would be a tedious as well as a laborous task. The basic principles involved seem to offer, at present, the only hope for directly determining the temperature of a re-entering body in a continuous manner (continuous in t) by the institution of optical measurement techniques. The spectrophotometer technique, however, is not as good a vehicle for implementing those principles as is photographic techniques. Where the radiation from the ablation products becomes significant, it will be necessary (with possible exception of the hydrogen-like atom case) to perform experiments on these products in order to establish data from which their contribution to the total spectral emission curve can be determined. This latter statement is also true for photographic techniques.

PHOTOGRAPHIC METHODS FOR MEASURING TEMPERATURE

The photographic technique for measuring the temperature of a re-entering object without spectral information is equivalent to the pyrometric technique, whereas spectral phototography is equivalent to the radiometer and spectrophotometer techniques. Thus, photography without spectral information is essentially useless for the direct measurement of the temperature of a re-entering body. The use of a spectral photograph in conjunction with a densitometer yields a plot which contains information that is equivalent to that from a spectrophotometer plot, the difference being that the densitometer gives the logarithym of the intensity instead of the intensity itself. The principal advantage of the spectral photography technique relative to the spectrophotometer technique is its inherently greater speed.

Otherwise, it suffers from the same shortcomings (physical phenomena constraints) as the spectrophotometry technique.

USE OF TRACER FLARES TO VALIDIFY BURN-UP MODEL

It is concluded that, without a detailed knowledge of the interactions of the flaring material with the re-entry environment which produce the light from tracer flares, the observations of the re-entry trajectories can neither prove nor disprove the validity of any particular mathematical model of re-entry burn-up. This stems from the fact that one cannot calculate the intensity of the light at any point along the trajectory without such knowledge (see eq. 29). For hydrogen-like flare materials (alkali metals), it is expected that the interactions giving rise to the emitted light could be calculated from a knowledge of the re-entry environment. The use of other flaring materials will require the institution of appropriate experiments before one will be in a position to calculate the magnitudes of the various interactions that produce the light from the re-entering flare. However, if the observed path length, position, and intensity profile of the flaring trajectory all agree closely with those predicted by the mathematical model, they would lend considerable credibility to its correctness.

Furthermore, this correlation could, if it is not considered to be fortuitious, yield valuable information on the excitation probabilities of the flaring atoms in the re-entry environment. Using this information, one could then devise a re-entry experiment which would either prove or disprove the validity of the re-entry model. The confidence in the predictive capability of a model, so established, in

its application to re-entering fuel elements will depend upon how closely the physical characteristics of the flares approach those of the fuel elements.

FLARE IDENTIFICATION

The analysis shows that a series of black and white photographs, each of which contains an image of every one of two or more simultaneously re-entering tracer flares, cannot, in general, be employed to positively identify each of the flares. This stems from the fact that the intensity of the light at any point along the re-entry trajectory cannot be determined beforehand without resorting to laboratory experiments to produce unavailable data. (Alkali metals may be an exception.) However, it is pointed out that if n photographs are taken of n re-entering flare trajectories, each of which completely extinguishes the light from a different one of the flares, each flare can be uniquely identified. Alternatively, each of the n cameras could pass the light emitted by one and only one of the flares, with each passing the light from a different flare.

Further, if only a snapshot color photograph, which reproduces the true colors, is taken of the flares, and if each of the flares emits light of a predomi-nantly different color, then the single photograph will be sufficient to uniquely identify each flare. Finally, a spectral photograph will produce the same results as a color photograph, providing, of course, that the spectra from two or more flares do not overlap on the photograph.

36

REFERENCES

1. Meggers, Corliss, and Scribner, Tables of Spectral Intensities, NBS Mono-graph 32 (29 December 1961), U.S. Government Printing Office, Washington, D.C. Price: $4.00.

2. Condon and Shortley, Theory of Atomic Spectra, Cambridge Univ. Press, London.

3. Massey and Burhop, Electronic and Ionic Impact Phenomena, Oxford Univ. Press, London.

4. J. W. Chamberlain, Physics of the Aurora and Airglow, Academic Press, N.Y., N.Y. (1961).

5. G. Hertzberg, Molecular Spectra and Molecular Structure, Vol. I, Spectra of Diatonic Molecules, Van Nostrand, N.Y., N. Y. (1950).

6. B. Kivel and K. Bailey, Table of Radiation from High Temperature Air, AVCO Research Report 21.

7. R. L. Trimpi and R. A. Jones, NASA TR-R-63 (1960).

8. C. E. Wittliff and J. T. Curtis, Cal. Rept. No. CAL-111 (Nov. 1961).

DISTRIBUTION

No. Cys

HEADQUARTERS USAF

1	USAF Dep, The Inspector General (AFIDI), Norton AFB, Calif
1	USAF Directorate of Nuclear Safety (AFINS), Kirtland AFB, NM

MAJOR AIR COMMANDS

1	AFSC (SCT), Andrews AFB, Wash 25, DC
1	AUL, Maxwell AFB, Ala

AFSC ORGANIZATIONS

1	ASD (ASRMFP), Wright-Patterson AFB, Ohio
1	RTD (RTN-W, Maj Munyon), Bolling AFB, Wash 25, DC
	SSD, AF Unit Post Office, Los Angeles 45, Calif
1	(SSTRE)
1	(SSZMS)
1	AF Msl Dev Cen (RRRT), Holloman AFB, NM

KIRTLAND AFB ORGANIZATIONS

1	AFSWC (SWEH), Kirtland AFB, NM
	AFWL, Kirtland AFB, NM
25	(WLL)
1	(WLR)
2	(WLDW)
2	(WLDN)
2	(WLDC)

OTHER AIR FORCE AGENCIES

3	Director, USAF Project RAND, via: Air Force Liaison Office, The RAND Corporation, 1700 Main Street, Santa Monica, Calif

DISTRIBUTION (Cont'd)

No. Cys

NAVY ACTIVITIES

1   Commander, Naval Ordnance Laboratory, ATTN: Dr. Rudlin, White Oak, Silver Spring, Md

1   US Naval Weapons Evaluation Facility (NWEF) (Code 404), Kirtland AFB, NM

OTHER DOD ACTIVITIES

20   Hq Defense Documentation Center for Scientific and Technical Information (DDC), Comeron Stn, Alexandria, Va 22314

AEC ACTIVITIES

4   US Atomic Energy Commission, ATTN: DRD/Asst Director for Compact Systems, Mail Station G-017, Wash 25, DC

4   US Atomic Energy Commission, ATTN: DRD/Asst Director for Nuclear Safety, Mail Station G-017, Wash 25, DC

6   Sandia Corporation, ATTN: Mr. V.E. Blake, Sandia Base, NM

1   US Atomic Energy Commission, Canoga Park Area Office, P.O. Box 591, Canoga Park, Calif

1   University of California Lawrence Radiation Laboratory, ATTN: Mr. Clovis G. Craig, P.O. Box 808, Livermore, Calif

OTHER

1   OTS, Department of Commerce, Wash 25, DC

3   Battelle Memorial Institute, ATTN: Mr. E.L. Foster, 505 King Avenue, Columbus 1, Ohio

1   Institute of the Aerospace Sciences, Inc., 2 East 64th Street, New York 21, NY

10   General Dynamics/Astronautics, ATTN: Mr. E.J. Philbin, P.O. Box 1128, Mail Zone 596-2, San Diego 12, Calif

6   Stanford Research Institute, Menlo Park, Calif

3   Vidya Research and Development, ATTN: Mr. W.J. Fleming, 2626 Hanover Street, Palo Alto, Calif

DISTRIBUTION (Cont'd)

No. Cys

3	Astropower, ATTN: Dr. A E. Levy-Pascal, 2968 Randolph Avenue, Costa Mesa, Calif
3	Westinghouse Electric Corporation, Astronuclear Laboratory ATTN: Mr. Alexander L. Feild, Jr., 250 Mt. Lebanon Blvd., Pittsburgh, Pa
3	Armour Research Foundation, ATTN: Mr. Jack Hedge, 10 West 35th Street, Chicago 16, Ill
10	Space Information Systems Division, North American Aviation, Inc., 12214 Lakewood Blvd., Downey, Calif, ATTN: Mr. Mark Morris, Dept 468
3	General Technology Corporation, ATTN: Mr. J.D. Graves, 2302 Willowood Lane, Alexandria, Va
3	AVCO Corporation, ATTN: Dr. J.G. Lundholm, 201 Lowell Street, Wilmington, Mass
6	Aerospace Corporation, (Library Tech Documents Group, ATD 61-5729 Technical Information Center) P.O. Box 95085, Los Angeles, Calif
2	Aerojet-General Nucleonics, ATTN: Mr. J.P. Lehman, Fostoria Way, San Ramon, Calif
1	Heliodyne Corporation, ATTN: Mr. Saul Feldman, 2365 Westwood Blvd., Los Angeles 64, Calif
1	Official Record Copy (Capt. C.E. Brunson, III, WLDN-2)

Air Force Special Weapons Center, Kirtland AF Base, New Mexico
Rpt. No. AFSWC TDR 63-58. INSTRUMENTATION STUDY AND ANALYSIS FOR OBSERVATION OF RE-ENTRY PHENOMENA. 43p, 3 refs. July 1963.

Unclassified Report

This work was undertaken to evaluate instrumentation and techniques for observing the phenomena associated with the atmospheric re-entry, at orbital or near orbital velocities, of NAP systems, with emphasis being placed on fuel element re-entry burn-up phenomena.

The uses of pyrometry, radiometry, spectrophotometry, and photography for determining the temperature of a re-entering body are analyzed. It is shown that all but the first of these methods can be used to obtain temperature infor-

1. NAP
2. Photography
3. Pyrometry
4. Radiation -- Measurement
5. Radiometers
6. Reactor fuels -- Testing
7. Re-entry
8. Spectrophotometric analysis
9. Temperature testing -- Test equipment
10. Test equipment -- Testing
I. AFSC Project 1331, Task 133103
II. Contract AF 29(601)-5390
III. General Technologies Corp., Alexandria, Va
IV. H.M. Childers
V. In DDC collection

Air Force Special Weapons Center, Kirtland AF Base, New Mexico
Rpt. No. AFSWC TDR 63-58. INSTRUMENTATION STUDY AND ANALYSIS FOR OBSERVATION OF RE-ENTRY PHENOMENA. 43p, 3 refs. July 1963.

Unclassified Report

This work was undertaken to evaluate instrumentation and techniques for observing the phenomena associated with the atmospheric re-entry, at orbital or near orbital velocities, of NAP systems, with emphasis being placed on fuel element re-entry burn-up phenomena.

The uses of pyrometry, radiometry, spectrophotometry, and photography for determining the temperature of a re-entering body are analyzed. It is shown that all but the first of these methods can be used to obtain temperature infor-

1. NAP
2. Photography
3. Pyrometry
4. Radiation -- Measurement
5. Radiometers
6. Reactor fuels -- Testing
7. Re-entry
8. Spectrophotometric analysis
9. Temperature testing -- Test equipment
10. Test equipment -- Testing
I. AFSC Project 1331, Task 133103
II. Contract AF 29(601)-5390
III. General Technologies Corp., Alexandria, Va
IV. H.M. Childers
V. In DDC collection

mation on re-entering objects that are not ablating. This temperature information is gained from measurements on the shape of the thermal emission curve. Methods for handling the ablating case are discussed.

The use of photography for identifying tracer flares that are re-entering the earth's atmosphere at high velocities was analyzed and shown to be feasible. How photography, in conjunction with tracer flare re-entry experiments, can be used for establishing the validity of mathematical, re-entry, burn-up models was also analyzed. The various associated difficulties and how they might be overcome are discussed in some detail.